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Introduction

EXPLORATION and utilization of space, both near Earth and within the solar system, and eventually, interstellar, is a continuing national interest. A major key to the effective utilization and exploration of space is an efficient, convenient, and cost-effective launch system into low Earth orbit. While major strides are being made in payload miniaturization, launcher performance/cost will remain a critical issue. One set of options for more effective launchers involves air-breathing propulsion, perhaps operating over portions of the ascent in a "combined cycle" mode. A particularly critical component of hypersonic air-breathing propulsion systems is the combustor, which is, historically, heavy due to requisite size/length and high aerodynamic and thermal loading and responsible for major portions of the total engine losses. One of the prime determinants of combustor efficiency is the distance required to "mix and burn," and therefore, effective mixing enhancement (including adequate fuel penetration) can provide a significant contribution to the viability of air-breathing hypersonic propulsion.

The penetration and mixing enhancement problem for hypersonic air breathers must obviously be worked within the context of overall engine efficiency and thrust production. There are a multitude of extant mixing enhancement techniques,^{1,2} the problem is obtaining a resultant net performance enhancement when the additional losses associated with the mixing enhancement approach are accounted for. At the higher

speeds (e.g., $M > 12$) the thrust imparted to the vehicle from the fuel injection process is increasingly important,³ requiring nearly parallel injection, a process that is not conducive to rapid mixing. The high Mach number end is also increasingly sensitive, in terms of net thrust, to losses of all types, mitigating against the use of instream injection struts with their high wave drag and heat transfer losses. The mean shear between the fuel jet and local stream flow becomes small in the Mach 12–15 range due to the high efflux speed of the regeneratively heated hydrogen fuel, further reducing the innate shear-induced mixing, but reducing the "convective Mach number." Therefore, in terms of criticality and payoff, the high Mach number range is the most important (air-breathing) regime for mixing enhancement.

The overall mixing problem in the combustor is nonsimple. The mean flow entering from the inlet is highly three dimensional and replete with unsteady shock and expansion waves, thick turbulent boundary layers, and embedded vortical entities. The combustor itself contains multiple fuel injection sites whose individual character could be different and whose three-dimensional flowfields interact with each other and with the incident flow, along with various types of possible front-side cooling-induced flow phenomena. These flow features and their interacting combinations are quite different from the simplex flows employed in most (laboratory, shear-dominated) mixing enhancement studies.

Mixing enhancement for engine performance improvement is the totality of increased micromixing (from small-scale turbulence/molecular mixing), increased "contact area" between air and fuel in a global sense (from "stirring" and multiple injection sites), and increased "path length" (e.g., from swirl). Known parameters having a first-order effect upon turbulent shear layers, and therefore, candidates for incorporation into synergistic mixing enhancement schemes, include pressure gradients, flow curvatures, energy release, proximity to transition/Reynolds number, shock/expansion waves, three-dimensional mean flow details, compressibility, adjacent surfaces, and stream fluctuation fields. Fuel distribution is also influenced by injection location(s) and approaches and action of "inviscid" wave systems. From these considerations an approach to scramjet mixing enhancement can be suggested that involves synergistic utilization of pre-existing flow features along with stirring and low loss turbulence enhancement approaches, all in the context of injection techniques consistent with achieving the required fuel coverage/penetration and fuel thrust. In particular, utilization should be made of the initiation and encouragement of innate instabilities that affect flows that are already turbulent (e.g., the Gortler instability, etc.).

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Hypervelocity Mixing Enhancement Suggestions

The current "best bet" for mixing enhancement in the high hypersonic air-breathing combustor case is the addition of organized longitudinal vorticity, possibly via raised ramp injectors.⁴⁻¹³ A summary of currently envisaged and potential benefits of this approach include the following:

1) Increased fuel-air interfacial area, if the fuel-air is entrained into the vortex.

2) Longitudinal vorticity-induced mixing enhancement via Rayleigh/curvature destabilization.¹⁴⁻¹⁸ This turbulence enhancement mechanism is relatively independent of Mach number, is effective over long downstream distances, and requires unstable velocity and density gradients. If not specifically tailored for destabilization, this mechanism can reduce, rather than increase mixing.

3) Increased penetration via mutual (multiple) vortex induction/interaction.^{19,20}

4) Significant realization/utilization of fuel thrust.

5) Possibility of major localized turbulence enhancement through vortex bursting via interaction with existing (inlet/injection-generated) wave systems.²¹⁻²³

6) Possible additional destabilization via multiple vortex interactions²⁴ and additional flow curvatures induced by such interactions.²⁵⁻²⁹

7) Facilitates utilization of incident (especially boundary-layer) turbulence fields via roll-up into vortex structures during formation process.³⁰⁻³⁷

Several longitudinal vorticity generation techniques/approaches are available including (from weak-to-strong circulation) Taylor-Gortler instability, jet injection(s),^{38,39} baroclinic torque (especially from shock interaction),⁴⁰ and discrete physical vortex generators from small-to-large scale (e.g., ramps,⁴⁻¹³ and mixing lobes.⁴¹⁻⁴⁷). Organized vorticity can be generated, using these techniques, in the incident combustor flow within the fuel jet⁴⁸⁻⁵⁴ or due to the fuel injection process(es).^{38,39,55} Additional longitudinal vorticity generation approaches specific to the fuel jets include circular-to-elliptic internal (longitudinal) geometry change¹ and jet swirl. Except for the Taylor-Gortler instability, these longitudinal vorticity generation techniques are based upon generation of transverse pressure gradients. The "approaches of choice," at least thus far, for the high hypersonic case are "swept ramps" and angled jet injection with secondary use of baroclinic torque. Up to now there has been little use of the various physics and synergisms allowed by the presence of multiple/interacting injectors/vortices, the exception being Ref. 56.

There are several obvious drawbacks/losses/problems associated with the generation and use of organized longitudinal vorticity for mixing enhancement. These include localized interference heat transfer, degradation of film cooling due to vortex interaction, thrust loss to cross-plane momentum, and ramp (shock/base pressure) drag and heat transfer losses.

The following approaches may increase the effectiveness of the longitudinal vorticity approach to combustor mixing enhancement for the high Mach number case:

1) Utilization of favorable interference between multiple injection-induced flowfields, e.g., wave drag reduction via favorable wave interference (side-to-side and across the duct) in the manner of the "Busemann Biplane," and vortex-vortex interaction to create "up-welling"/enhanced penetration (may allow reduced ramp size/losses).

2) Design for Rayleigh destabilization (especially within the vortex flows), may require injection and entrainment of fuel into the vortex systems during their formation process(es). Simplistically, requires negative gradients of velocity/density with increasing radius within the vortex.

3) "Unwinding" of the organized vorticity via interaction with oppositely signed vorticity prior to exit of combustor to minimize thrust loss due to cross-stream velocity fields.⁵⁷ Also, incorporation of other (including nonlinear, three-dimen-

sional) instability modes that are effective in a turbulent environment.

4) Vortex generation processes designed to facilitate entrainment of wall boundary-layer turbulence into the mixing process.

5) Incorporation of longitudinal vorticity generation within the fuel streams.

6) Optimized number and location of injection sites and types for multiple metrics including favorable interactions, increased interfacial area, penetration/fueling, and overall metrics such as thrust level and combustor weight/complexity.

7) Utilization of fuel underexpansion as an aid to penetration and overall efficiency.⁵⁸

The parameter space for an optimized combustor (as opposed to an injector) is, unfortunately, immense. Variables include scale(s)/locations/numbers/types of vortex generation sites as well as their relationship(s) to fuel injection sites/injector types and the multiplicity of their mutual interactions. The applicable metrics are also nonsimple and include weight, size, heat transfer, friction, and wave loss reduction as well as minimization of design complexity/cost, all in the context of thrust/ I_{sp} maximization, operability across the speed range, and incorporation of integral rocket/combined cycle features at even higher speeds. Obviously, the problem of mixing enhancement/combustor design for this high-speed case has little relationship to conventional laboratory studies of single enhancement techniques applied to two-dimensional shear-driven mixing.

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